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# RIVETED JOINTS IN THIN PLATES

By W. Hilbes

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS.

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# RIVETED JOINTS IN THIN PLATES.*

By W. Hilbes.

It is common practice in metal airplane construction to join all structural components by riveting. But in this comparatively new branch the experience gained in iron construction is of no avail, because the conditions are wholly dissimilar. The relation of plate thickness to rivet diameter and the strength factors in the structural materials intended for metal aircraft are essentially different from that for steel, etc. In addition, our information on test data of riveting heat-treated light metals as applied to aircraft construction, is not complete, so an examination of the actual conditions may not be amiss.

There are two principal methods of riveting. The closing head is formed under increasing pressure or by a series of hammer blows. We confine ourselves to the former method.

Both test specimen and rivets were of ultralumin (U II alloy), an annealable, artificially aging alumin-copper- nickel alloy. Plates and rivets were heated for an hour at 535°C, and then water-quenched. The plates were artificially aged for 40 hours at 120°C. The obtained tensile strength was 36-37 kg/mm²

*"Ueber die Nietverbindung dünner Bleche." From Jahrbuch der Wissenschaftlichen Gesellschaft für Luftfahrt (W.G.L.), 1929.

by ~ 20% elongation, although considerably higher values are obtainable according to more recent reports. The rivets were used un-aged and quenched, because of the impossibility of forming a correct closing head with normally heat-treated rivets due to their increased hardness. The shape of the rivet was a flat half-round head, according to specification 660. The test specimens, made as single shear lap rivet joints, carried only one rivet to make the conditions as clear and simple as possible.

Any possible danger of different frictional changes, caused by turning of both halves of the specimen with respect to each other, was perfectly controlled by the two tensiometers shown in Figure 1, which indicated the slippage of both riveted halves. Any twisting during tension stress, caused by wrong restraint, was immediately shown on the two instruments.

To ensure the optimum conditions of the ratio:- rivet diameter d to plate thickness s - we made a number of tear tests on various rivet-and-plate thicknesses.

In judging the conditions we used the ultimate stress of the joint as criterion. But, as we found later, this load is dependent on the chosen distance of the rivet from the edge athwart the direction of the stress. To obviate this effect, we chose a third edge distance. The closing pressure was gauged to allow satisfactory forming of the closing head. Under tear the destruction of the joint occurred in the ratio of d : s, either by shearing off the rivet in the plane between both plates, or by tearing of the plate tangential to the direction of stress of the rivet hole. Figure 2 shows the ultimate stress plotted against the rivet diameters. The breaks follow a parabola which is characterized by the shearing strength of the rivet material. The curves for the plate failure represent exponential functions, in which the ultimate stresses are affected by d, s, the tensile strength of the material, and by the closing pressure. The intersections of these breaking curves with the rivet failure parabola denote the rivet diameters in which the strength of rivet and plate is evenly absorbed. But to use such diameters is not good shop practice, particularly for thin plates. In this case we could use rivets of the same alloy but quenched at lower temperature. The shearing strength is lower, therefore the rivet failure parabola is flatter. To form a closing head with so much softer material requires less pressure, which would at least reduce, if not prevent the tendency of the plate to warp around the hole.

The effect on the shearing strength of clinching the rivet body while forming the second head was investigated on four cylindrical specimens made of the same material and heat-treated like the rivets. Two were first clinched 15% under pressure. The ultimate stresses were

$$\text{Plain:} \qquad \tau_B = \left.\begin{matrix}19.1\\19.7\end{matrix}\right\}\text{kg/mm}^2$$

$$\text{15\% clinched:} \qquad \tau_B = \left.\begin{matrix}21.6\\21.0\end{matrix}\right\}\text{kg/mm}^2$$

The parabola for a 21.3 kg/mm² mean shearing strength has been included in Figure 2. The discrepancy in the two curves is due to the fact that the ultimate stress refers to the nominal instead of to the actually obtained diameters. This same diagram further shows various values of failure in shear as determined by Gabrielli in his measurements on duralumin riveted joints.* When the specimens did not tear directly after riveting, i.e., prior to aging, we are justified by reason of these test data, to conclude that the aging process was at least violently interrupted by the cold clinching of the rivet body because the maximum stress obtained was far below the figure expected for normally aged duralumin.

The question as to the best edge distance, i.e., that distance from the rivet center to the plate edge below which it is inadvisable to go and, at the same time useless to go beyond, was examined as follows:

Since it was a matter of relative behavior of obtained maximum stress by increasing edge distance, we used no riveted specimens. Instead of the usual rivet body and heads, we used a cylindrical steel bolt and steel rings of the same diameter as the original. The set-up was as shown in Figure 3. A slightly tightened nut at the end of the bolt insured adequate protection of the relative position. The ratio d : s was chosen according to the ultimate stress diagram and in such a manner that

*Atti Del Congresso Annvale, Torino, 1928.

the failure occurred in the plate. We determined the tearing stress in various test series for different edge distances, and plotted the results in Figure 3.

The individual points represent mean values for four individual tests each. By small edge distance the piece between the rivet and the plate edge sheared off. The data agree with the calculation for 27 kg/mm² shearing strength of the plate when assuming a cross section

$$P_B = \tau_B \quad s\ 2\left(e - \frac{d}{2}\right)$$

as indicated by Bach. The tearing occurs as tearing of the fiber tangential to the rivet hole in the direction of the stress. Within 5-8 mm edge distance we note a pronounced scattering of the test values. This is due to the tendency of the plate in front of the rivet to buckle, once a certain critical ratio of plate thickness to edge distance, or more exact, of $s : e - \frac{d}{2}$, has been reached. If the specimen remains flat up to failure, the obtained stress values are higher than if preceded by buckling. Any further increase in $e$ results in buckling, and the ultimate stress remains constant. Assuming the edge distance of the shear failure curve intersection with the tearing failure curve as limit value, the result is as shown in Figure 4.

These obtained optimum values for $e$ are, strictly speaking, applicable only to cases in which the plate fails. But during the investigation it became apparent that with riveted joints which are at the uppermost limit of rivet failure, and which had been made with the best edge distance for plate failure, the piece of the plate in front of the rivet suffers pronounced, permanent deformation by bending in the plane of the plate if the joint is destroyed. For that reason it does not appear advisable to go below the value obtained above.

So far, we have discussed the factors deciding the structural end of a riveted joint. But the ultimate stress does not give any indication of the behavior of the joint within the lower stress limit. According to Preuss, permanent slippage between the plates occurs in boiler riveting, even under low stress. Although this slippage does not play the same role in airplane riveting as it does in boiler construction, the possibility remains that such permanent deformations occur in riveted joints under peak stresses in structural members, so the assumptions upon which the static calculation is based, become invalid.

Figure 5 shows the deformation of a riveted joint according to the tests. The slippage of the plates which occurs under the effect of a certain stress, does not completely disappear upon unloading. Under repeated stressing, the slippage follows the unloading curve quite faithfully until the previous load maximum is reached.

The elastic form change is essentially a function of the elasticity modulus, the slip modulus, the supporting moment, the rivet spacing, etc, which we shall not discuss here, however.

Schroder von der Kolk's method of measuring the permanent slippage in iron riveted joints* is too far-fetched. Preuss' method**, although decidedly more accurate, is applicable to thick plates only. So a different method had to be devised. (See Figure 1.) The actual measurement was made with the normal 1 : 1000 Huggenberger tensiometers. By gauging of tenths-scale units, the deformation can be read to 1/1000 mm. The two tensiometers were placed symmetrical to the principal axis of the specimen, and at a distance from the rivet. This permitted the assumption that the stress at the test points was below the elastic limit. To avoid all additional stresses through the weight of the apparatus itself, we resorted to lever and counterweight.

The specimens had a preliminary stress of 5 kilograms in these tests. Readings were made for the same stress after each stress stage. Figure 6 shows the slippage of two riveted joints, which were destroyed by rivet failure. The curves indicate the appearance of permanent deformations even under very low stresses. One outstanding factor is the effect of the closing pressure, which enables us to draw several conclusions on the conditions closest around the rivet.

Then we made several fine measurements on specimens riveted under different closing pressures. After plotting the slippage

*Zeitschrift des Vereines deutscher Ingenieure, 1897, pp. 739-747; pp. 768-774.

**Zeitschrift des Vereines deutscher Ingenieure, 1912, p. 405.

curve, we stressed to failure, which occurred in the plate depending on the d : s ratio. The diagrams of Figure 8 show the slippage curves for the individual closing pressures, each representing the mean value from three tests, as well as the obtained ultimate stress, where the effect of the closing pressure on the slippage becomes readily apparent. One surprising feature is that the slippage at first decreases by increasing closing pressure, and does not begin to show any rising tendency below 1500 kilograms. The explanation of this strange behavior in slippage is:

Under a 500-kilogram closing pressure, which here corresponds to a specific pressure of 32 kg/mm$^2$, the pinching limit in the rivet has been so far exceeded that the body of the rivet fills the rivet hole completely. The free end of the rivet is slightly barrel-shaped. For permanent deformation the fiber, tangential to the rivet hole in the direction of the stress, must be stressed beyond the elastic limit by simultaneously overcoming the slippage existing between the two plates.

The compression stress in the hole wall is much lower. An increase in closing pressure leads to transverse elongation of the rivet body within the plates. This produces compression stresses acting radially on the hole wall, which result in tension stresses concentric to the rivet hole. These stresses are augmented by perpendicular compression stresses parallel to the rivet axis, produced by complete shaping of closing head in the plate. In consequence, the stress in the already endangered fiber is in the same direction as the working stress, and it needs but a slight additional stress to permanently deform this fiber. By any further increase in closing pressure the compression stresses acting in the plate likewise exceed the pinching limit; this is the beginning of cold hardening which increases the strength of the joint, as may be seen on the ultimate stress curve. Up to about 1500 kg closing pressure, the ultimate stress is almost constant; from here on, it raises on account of the deformation of the plate, that is, according to the degree of hardening. Further examination shows the extent to which these data may be applied to whole groups of rivets.

In framework structures, it is common practice to transmit the existing stresses through several successive rivets to the junction points. The behavior of such type of riveting is illustrated in Figure 8. With two rivets the slippage within the lower stress limit is twice as high as in the single riveting. Moreover, the rivet spacing has no appreciable effect on the deformability of the joint.

In one specimen the section of the plate between the two rivets showed a slight bulging. This did not change the ultimate stress.

This information represents the data to date of the investigation which is now being made by the Aerodynamic Institute of the Technical High School, Aachen. Further results are to be published in detail in a future issue of the Z.F.M. (Zeitschrift für Flugtechnik und Motorluftschiffahrt).

These tests were made possible by the generosity of the Relief Society for German Science, which placed the necessary means gratuitously at our disposal.

## D i s c u s s i o n

Dr. W. Pleines: I wish to supplement Mr. Hilbes' treatise by a few remarks, which cover only a fraction of the tests which I made between 1926 and 1929, with the cooperation of the D.V.L., and which included a stay of several months at the Junkers and the Rohrbach metal airplane factories.*

Regarding Mr. Hilbes' shearing-strength tests on light metal rivets, I particularly wish to call attention to the fact that the shearing strength of rivets in duralumin depends not only on the material of which the rivet is made (use of various alloys), but on the kind of rivet, treatment, and riveting by hand or machine.

Dr. H. G. Bader: In connection with the report of the speaker, on riveted joints in light metal construction, I wish to call attention to certain practical mathematical short-cuts. It very often happens, particularly through the limited dimensions in light structures, that in addition to stresses, turning moments occur

*Von W. Pleines, "Nietverfahren im Metallflugzeugbau." Luftfahrtforschung, Vol. VII, and Jahrbuch 1930, D.V.L. (For translation, see N.A.C.A. Technical Memorandums Nos. 596-599, Parts I-IV: Riveting in Metal Airplane Construction.)

in the gusset plate. In that case we find different additional stresses in the individual rivets, which, regardless of whether crushing or shearing, can be assumed as proportional to the distance of the individual rivet from the center of gravity of the rivet group. The contribution of each rivet toward the total moment of the group of rivets, which must equal the moment of the outside stresses, is found by multiplying the stress of each rivet with its leverage with respect to the center of gravity of the rivet group. It increases by the square of the specified distance r. So, for computing the stress of the most endangered rivet we need the polar inertia moment of the rivet cross sections with respect to the center of gravity of the rivet group. This calculation, repeated several hundred times for a larger airplane, is usually made scalar, first determining the center of gravity of the rivet and then the inertia moment after measuring the distances of the individual rivets.

Moreover, since the rivet arrangement within a junction plate must be plotted anyway, it is but a step to make the calculation graphically. The conditions here become so simple and clear, that it is possible to estimate the additional stress without making an accurate calculation.

We merely draw two funicular polygons for two axes perpendicular to each other. Instead of the forces in the stress diagram we simply plot the rivet cross sections. The horizontal stress, whose magnitude is arbitrary for the calculation, is defined by drawing the closing lines at 45°. Since it pertains almost without exception to groups of rivets with the same diameter, these polygons can be quickly drawn, and by closing them, with like content, by a horizontal line, the inertia radius is given by the height of the thus produced equilateral rectangular triangle.

The geometrical addition of both inertia radii for the axes at right angles to each other yields the polar inertia radius $i$. With $R$ as the resultant of the outside stresses, $F$ the total area of the rivet group, i.e., the sum of the cross sections and hole areas of all rivets belonging to the group, and $e$ the eccentricity of $R$ with respect to the center of gravity of the rivet group, the stress in each rivet is found from the vectorial addition of the stress by force and moment:

$$\sigma = \frac{R}{F} \xrightarrow{+} \frac{R}{F}\frac{e}{i^2} r$$

The stress due to the force is in its direction, and the stress through the moment is perpendicular to the respective distance $r$. Thus, expressing the distance $i^2/e$ by $a$, the formula becomes

$$\sigma = \frac{R}{F} \frac{a \xrightarrow{+} r}{a} = \frac{R}{F} \frac{b}{a}$$

So, when we consider distance $r$ graphically as measure of the stress, we simply plot distance $a$ perpendicular to the stress of the rivet, that is, perpendicular to resultant $R$ from the center of gravity of the rivet group. In that manner the stress is found from the vector sum of a and r in the scale of a. This vector sum, as we see in the diagram, is highest in the rivet with the greatest distance b from point a. (Inasmuch as the stresses in the rivets must be added vectorially, the rivet with the greatest distance r from the center of gravity of the group is not endangered most, as usually assumed in scalar calculation.) The ratio of b/a is the increase factor for the stress of the rivet most endangered with respect to a moment-free connection. This ratio can be easily estimated in a recurrent calculation, thus obviating quite often the exact graphic method.

Dr. K. Thalau: Within the "elastic limit" of a riveted joint the individual rivets contribute, according to their location, their different shares toward the total stress to be transmitted, while, shortly before reaching the static ultimate stress, the stress is about evenly divided over the individual rivets. Nevertheless, it is not always permissible because of the frequently existing alternate stress in such joints, to dimension the connecting rivet solely with respect to a uniform, static stress distribution, but it should be borne in mind that the rivets, stressed highest under one certain operating condition, are not to be stressed beyond their fatigue strength.

The difficulties of this type of computation lie in the assumption of the vibration amplitude, or in other words, in the determination of the amount of static stress and the superposing alternate stress, and in the determination of the safe alternate stress for such joints.

Mr. M. H. Bauer: When judging riveted joints, we must also take into consideration the manner in which these joints were made. The speaker failed to mention the play between hole and rivet before driving. This play, and the type of riveting, whether by hammering or press, has some effect on the strength of the whole, for which reason it should be invaluable to investigate it systematically. With large play, it requires longer hammering than with slight play, and it is not certain whether this hollow space is completely filled before the closing head is formed. This applies, in particular, to the part of the hollow space near the transition of the rivet body in the closing head.

Then the play will also affect the strength of a rivet row in absorbing stresses. Theoretically, each rivet should have the same strength. But in reality, each rivet has its own strength factor, depending on the circumstances under which it was made, and it is only in rare cases that all rivets of one row shear off at one time. Usually one rivet shears off first, and then the others, becoming overstressed, follow.

For these reasons, I advocate the inclusion of the effect of rivet clearance or play in the experiments. It will enable us to define the limits of safe play or clearance in rivet holes.

Mr. W. Hilbes: With respect to the fatigue strength of riveted joints, I wish to state that we lack the necessary fundamental bases for any systematic research of whole structural subassemblies for fatigue, as long as the behavior of the materials, particularly light metals under alternate stress, has not been conclusively explained.

My experiments on the effect of play between rivet body and hole wall have shown that within normal limits, i.e., of play = 0 - ~ 10% of rivet diameter, the ultimate stress is not perceptibly changed. When forming the closing head, the material of the rivet body yields until the hole is completely filled, i.e., ordinarily there is no play when the riveting is finished.

The tests published here form, of course, only the primary principles for testing whole junction points. As already stated, when closing my report, the tests of whole rivet groups are in abeyance.

I am glad to hear that Dr. Pleines' experiments, made at the D.V.L., have shown similar results to the Aachen tests. We shall soon have an opportunity to make more exact comparisons.

Translation by J. Vanier,
National Advisory Committee
for Aeronautics.

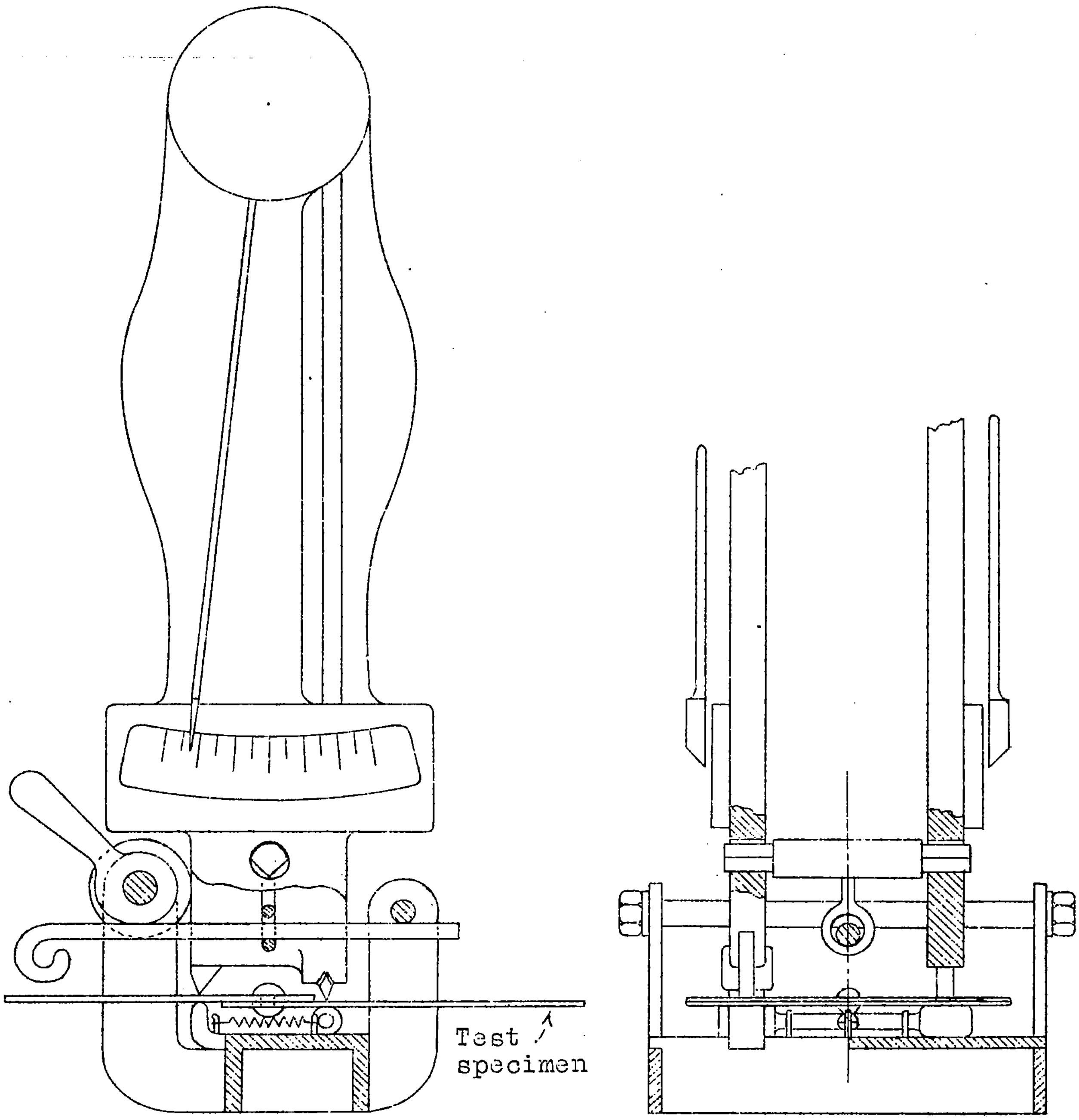


Fig. 1 Method of fastening specimen for testing the slippage on the tensionmeter.

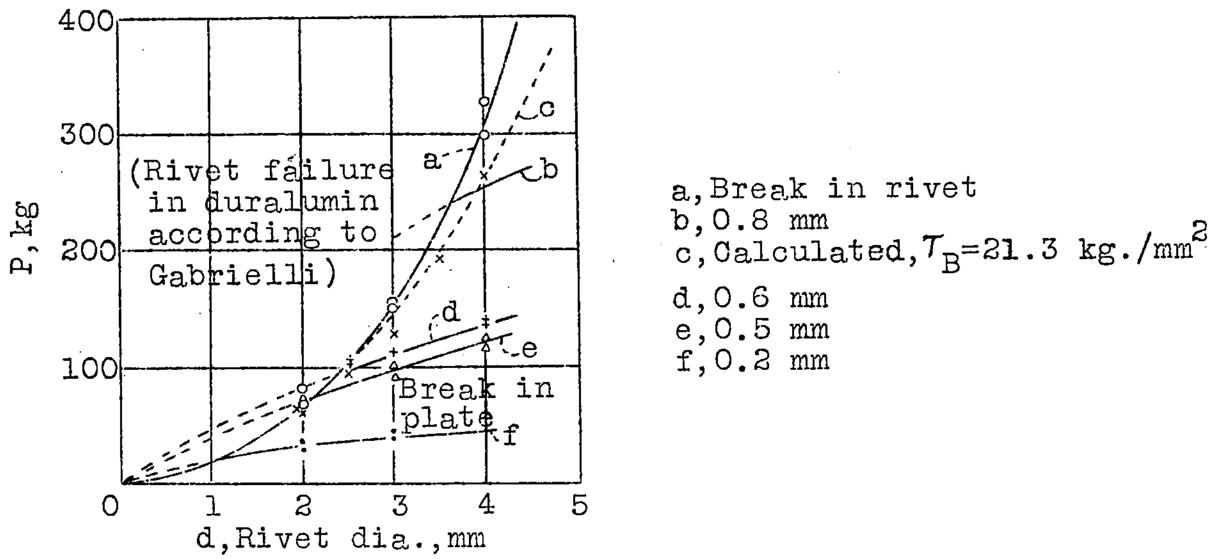


Fig.2 Ultimate stress diagram.

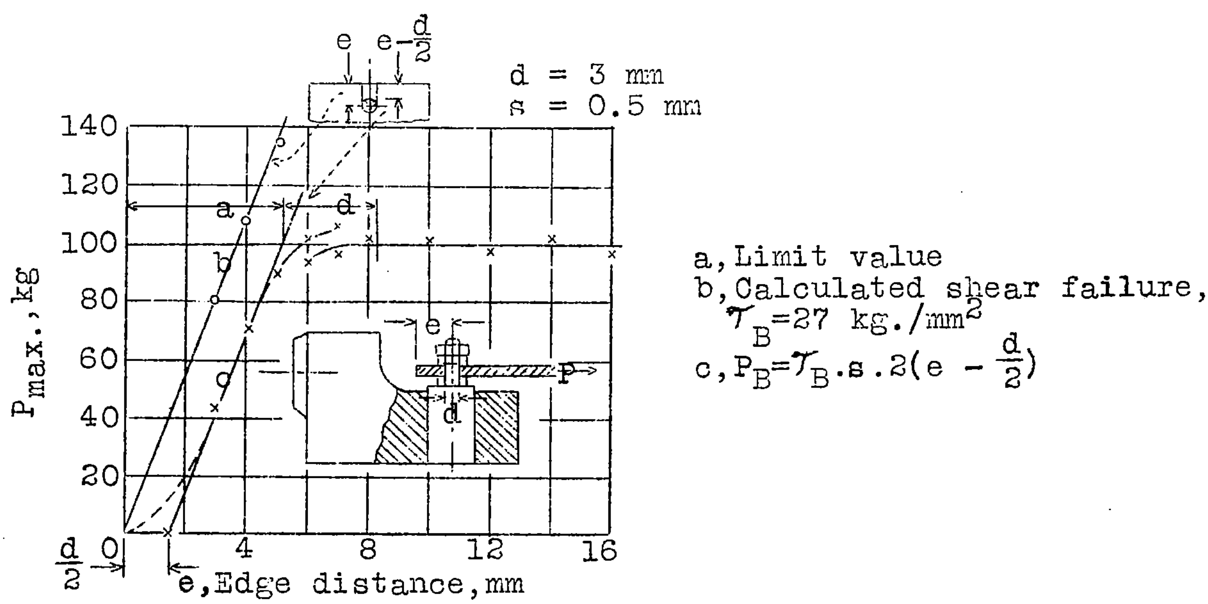


Fig.3 Effect of edge distance.

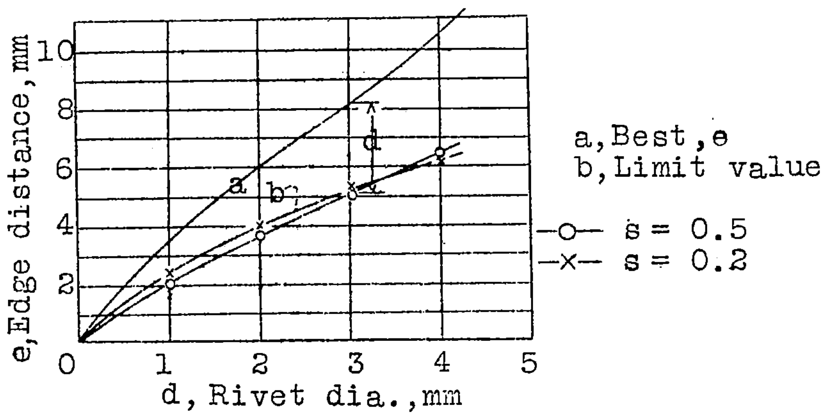


Fig.4

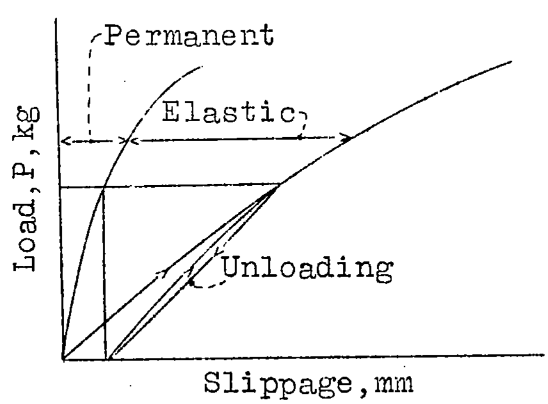


Fig.5 Deformation of riveted joint.

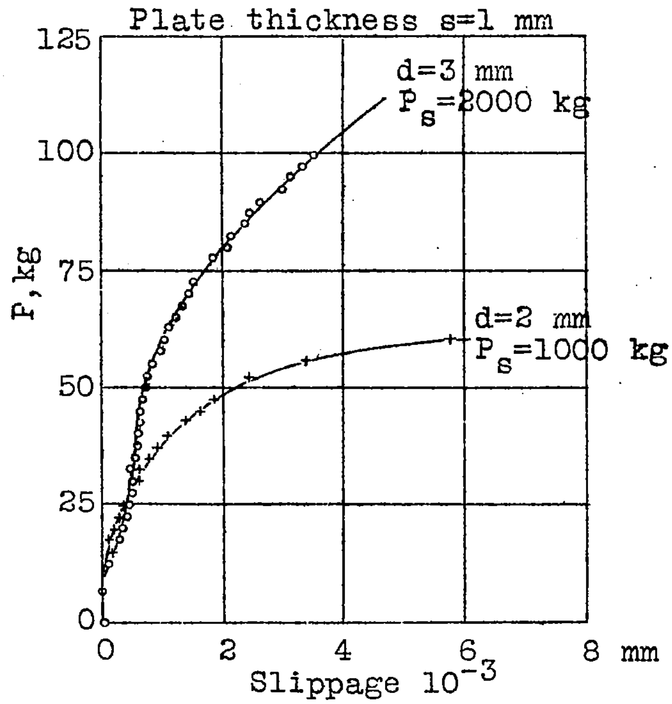


Fig.6 Slippage curves.

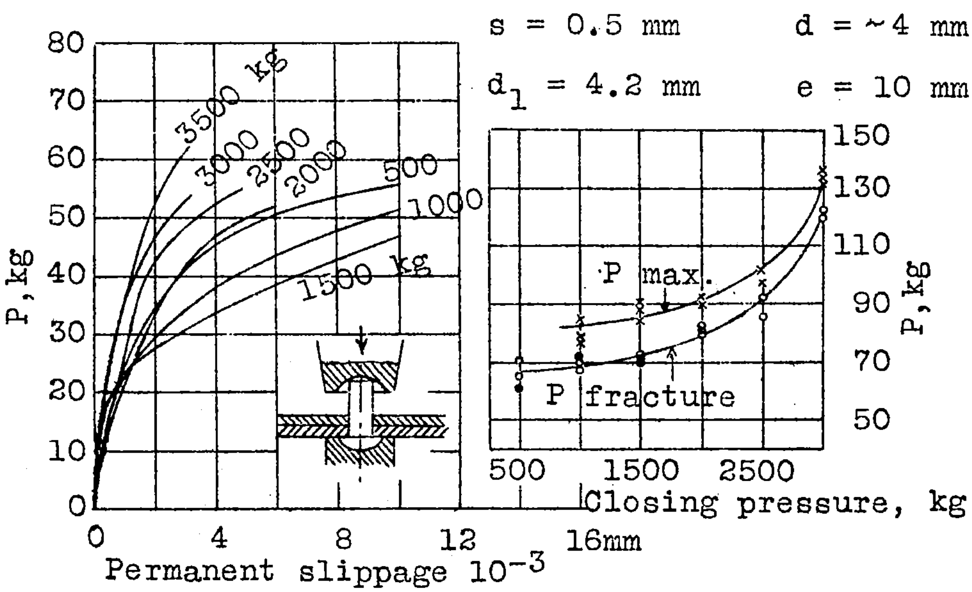


Fig.7 Effect of closing pressure. (Figures on slippage curves denote amount of closing pressure.)

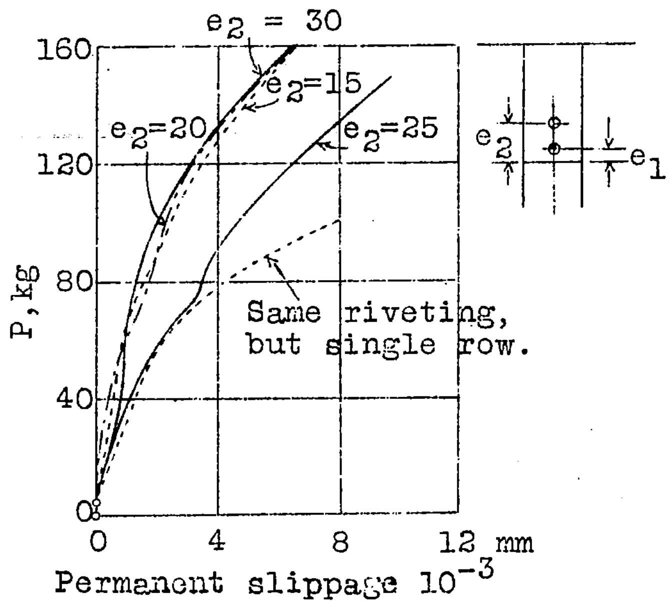


Fig.8 Slippage curve for double riveting.

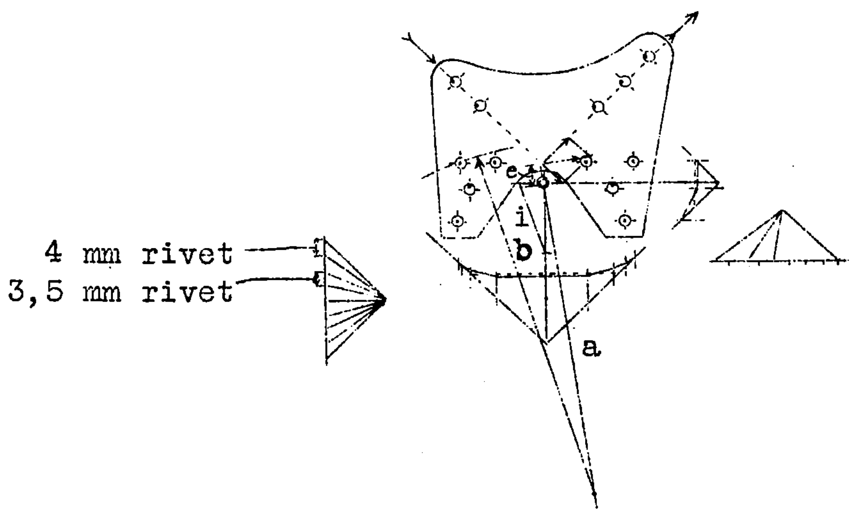


Fig.9